

REMARKS

Claim 3 of the substitute specification filed herewith is canceled without prejudice. Claims 1 and 2 of the substitute specification are amended herein prior to receipt of a first office action.

Two new consecutive paragraphs are added to the substitute specification.

The amendments to the claims parallel amendments made to German patent application 102 38 061.9-52 by the German attorney's letter dated August 1, 2003. The present application is the U.S. national phase of International patent application PCT/EP03/07830 that claims Convention priority from such German application. The German Patent Office has indicated that such amended claims can be granted.

The paragraphs added to the substitute specification constitute English language translations of corresponding additions to the specification of the above-identified German patent application made by the German attorney's letter dated December 30, 2003.

No new matter is added by any of the amendments made  
herein.

Respectfully submitted,

A handwritten signature in black ink, appearing to read "Elliott N. Kramsky", written over the printed name.

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Title: METHOD FOR DETERMINATION OF AND COMPENSATION FOR  
THE SCALE FACTOR ERROR CAUSED BY CHANGES TO THE  
WAVELENGTH IN A GPS-SUPPORTED INS SYSTEM

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BACKGROUND

Field of the Invention:

The present invention relates to GPS-supported inertial attitude and heading reference (INS-Systems) systems having Kalman filters. More particularly, this invention  
10 pertains to a method for determination and compensation of scale factor error in such a system due to wavelength changes in multiple-axis fiber optic gyroscopes having a common light source. ~~The invention relates to a method for determination of and compensation for the scale factor error caused by~~  
15 ~~changes in the wavelength in multiple axis fiber-optic gyroscopes (FOG) which are fed from a common light source, in a GPS-supported inertial track and attitude reference system (INS system) which is equipped with a Kalman correction filter.~~

20 Description of the Prior Art

~~For DE 196 51 543 C1 discloses the teaches~~  
subtraction of attitude and heading ~~track and attitude~~ angles produced by ~~means of the~~ a GPS receiver from the corresponding data supplied by an inertial sensor for  
25 iterative correction ~~assessment~~ of a platform calculation by means of a Kalman filter, in an attitude and heading track ~~and attitude~~ reference system including ~~with~~ an inertial system that is assisted by means of a GPS receiver. Such method obtains ~~order to obtain~~ an accurate  
30 track/attitude/heading reference of comparatively wide bandwidth that is independent ~~independently~~ of acceleration

sensors. Correction models for GPS/INS mechanizations for ~~track and attitude and heading~~ reference systems in which whose INS values are corrected by ~~means of~~ a Kalman filter with different disturbance variables ~~also being considered~~ are known from the published book disclosed in Kayton and Fried, Avionics Navigation Systems, Second Edition (1997), pgs. 72-98.

~~In general~~ It is also generally known to estimate for the errors of inertial sensors (i.e., ~~the~~ zero error (bias), scale factor and axis alignment error) in INS/GPS systems ~~such as these to be estimated~~ with the aid of external information using a Kalman filter technique. Such ~~the possibility of~~ estimated values are then utilized to correct ~~used for correction of the~~ sensor data.

Satellite navigation systems, such as the United States Global Positioning System ("GPS") are particularly suitable ~~as purpose since~~ they provide the position and the velocity virtually continuously, with high accuracy and without any drift. Kalman filters make it possible to use the difference between the position and velocity data from the GPS and from the inertial system to estimate the inertial sensor errors of the, ~~in order to~~ and to thoroughly perform ~~carry out an~~ appropriate corrections ~~correction~~.

However as mentioned above, the determination of the sensor errors with the aid of external assistance ~~information~~ and Kalman filter techniques, is dependent upon on a specific amount of motion dynamics of the vehicle (e.g. an aircraft) as error mechanisms of the inertial sensors can only be stimulated in this way. They ~~and~~ can then be observed via the Kalman filter.

~~In general, these~~ Such vehicles generally move in  
on a horizontal plane, with pitch and roll movements assuming  
relatively large values for only a short time period. On the  
other hand, GPS reception is lost ~~entirely~~ during very major  
5 attitude angle changes (e.g. ~~when~~ aircraft ~~are~~ engaged in  
aerobatics) when the GPS antenna can no longer receive ~~the~~  
satellite signals. As a result, the scale factor can then  
~~now~~ no longer be estimated or determined satisfactorily.  
Furthermore, any increase in ~~the~~ scale factor error resulting  
10 from a change in the wavelength of the light source will  
become ~~becomes~~ evident only after the systems have been  
in use for a relatively long time.

The reduction in accuracy in ~~track/attitude/heading~~  
reference systems generally remains unknown as unidentified,  
15 ~~since~~ the system error is largely suppressed by vertical  
~~sensor~~ and magnetic sensor assistance, and has therefore ~~thus~~  
been found to be ~~technically~~ relatively insignificant.  
However, an improvement in ~~the~~ scale factor accuracy and ~~in~~  
its long-term stability is absolutely essential for future  
20 tasks, particularly in assisted inertial navigation and when  
attitude angle accuracy is subject to stringent requirements.

#### SUMMARY AND OBJECTS OF THE INVENTION

It is therefore an object of the invention to  
provide ~~The invention is thus based on the object of~~  
25 providing a method for improving ~~by means of which~~ scale  
factor accuracy, particularly for ~~in the case of~~ a GPS-  
supported inertial ~~track and~~ attitude and heading reference  
system ~~which is~~ equipped with a multiple axis fiber-optic  
gyroscope that is fed from a common light source.

The preceding object and others are addressed by  
the invention which provides ~~in the case of~~ a method for  
determining ~~determination of~~ the compensation for the scale  
error due to ~~caused by~~ changes in wavelength in multiple axis  
5 fiber-optic gyroscopes ("FOGs") fed from a common light  
source in a GPS-supported inertial ~~track and~~ attitude and  
heading reference system equipped with Kalman filter\  
correction. Such method utilizes ~~the invention uses~~ the scale  
factor error determined for one axis with relatively fast  
10 motion dynamics ~~being used~~ as the Kalman filter correction  
value for the scale factor error correction for all the  
measurement axes of the FOG having ~~with~~ slower motion  
dynamics.

The preceding and other features of the invention  
15 will become further apparent from the detailed description  
that follows. Such description is accompanied by a set of  
drawing figures. Numerals of the drawing figures,  
corresponding to those of the written specification, point to  
the features of the invention with like numerals referring to  
20 like features throughout both the drawing figures and the  
written specification.

~~The invention and advantageous details will be explained in  
more detail in the following text, using one embodiment by  
way of example, and with reference to the drawings, in which.~~

#### 25 BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is ~~shows~~ a functional block diagram of an  
inertial navigation system, supported by GPS data and  
including ~~with~~ Kalman filter correction; and

Figure 2 ~~is shows~~ a more detailed functional block diagram ~~for illustrating in order to explain the error correction, in particular scale factor correction, in accordance with based on the method of according to the~~ invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 1 is a functional block diagram of an inertial navigation system, supported by GPS data and including Kalman filter correction. The scale factor of a fiber optic gyroscope ~~or fiber gyro~~ within an inertial navigation system 10 is governed predominantly by two factors. The Sagnac phase, which is produced by an external spin rate in the FOG (not illustrated), is governed by the wavelength (or frequency) of light in the glass fiber and by the geometric dimensions of the fiber coil (the area enclosed by the winding). ~~Furthermore~~ In a resetting system, the scaling of the reset (scaling: rotation angle increment/Sagnac phase) in the fiber gyro control loop governs the scale factor.

Figure 2 is a detailed functional block diagram for illustrating error correction, scale factor correction in particular, in accordance with the method of the invention.

~~In the case of~~ a multiple (e.g. three) axis FOG architecture 2 ~~(see Figure 2), which is~~ fed from a common light source 1, electrical scale factor is determined and monitored by an auxiliary control loop 3 ~~of in~~ the FOG electronics. On the other hand, scale factor error, which ~~that~~ is influenced by the geometric/mechanical dimensions of the FOG sensor coils, is recorded by ~~via~~ the system calibration

(calibration data), and compensated for by means of a ~~an~~ FOG

error correction 4. The wavelength of the common light source 1 is ~~also~~ taken into account indirectly in such ~~this~~ system calibration and ~~Thus, in particular,~~ manufacturing errors are thus corrected. Changes in the wavelength of the common light source 1 during operation are no longer recorded. To this extent, the functional circuit diagram of Figure 1 illustrates the prior art, ~~which illustrates~~ an inertial navigation system 10 ~~that is~~ supported by a GPS navigation system 20 using a Kalman filter 30 in which ~~and~~ ~~whose~~ corrected navigation data on the output side is passed to a higher-level computer system.

The problems associated with ~~the~~ changes in scale factor that occur, for example, as a result of aging ~~effects~~ of the light source 1 are ~~, of course,~~ known. In the past, two relatively complex methods have been employed ~~used~~ to solve this problem. In the first method, a laser light source is utilized in which the spectrum required for FOG operation is produced by other ~~further~~ optical elements. ~~The primary expensive factor in this case is~~ The additional optical components add expense ~~as well as the fact that~~ ~~while~~ the lengths of fiber required is virtually twice as long as a result of ~~owing to~~ the longer wavelength of the ~~these~~ light sources. Another ~~proposed~~ option is direct measurement of the wavelength, making ~~which makes~~ it possible to compensate computationally for the associated scale factor error. The interferometric test layer ~~that is~~ required for this requires a number of additional optical and electrical components, again making ~~however, which make~~ the overall system considerably more expensive. No marketable and competitive solution employing ~~using~~ this option exists.



The invention makes use, inter alia, of the insight ~~discovery~~ that a change in the wavelength of the common light source 1 ~~which is~~ for all three measurement axes of a FOG triad has the same effect on all three measurement axes.

5 This is based on the idea, in accordance with ~~according to~~ the invention, ~~specifically~~ of also employing the scale factor error of the vertical measurement axis z, which can be accurately determined, for the two horizontal measurement axes x, y of the fiber-optic system.

10 One advantageous embodiment of the invention takes additional account of the fact that the horizontal axes x and y constitute ~~are~~ the governing factor ~~on the determination of~~ the safety-critical attitude angles so that the scale factor error correction should only be carried out with a long time  
15 constant. In this case, it is important that the change in ~~the~~ wavelength and, thus, the increase in ~~the~~ scale factor error, be caused by aging of the light source over a period of several months. ~~Until now,~~ The precise relationship between the period of use and the wavelength shift ~~has~~  
20 ~~admittedly~~ has not ~~yet~~ been previously investigated or statistically recorded. In addition to the time factor, ~~the~~ environment (temperature, vibration, etc) also exerts ~~has~~ a significant influence. When repairs are carried out, it has been necessary to replace light sources, or to recalibrate  
25 the system, after light source operating periods ~~times~~ of only 8 to 12 months. The time constant for correction of the Kalman filter should thus be in the range ~~between~~ 10 and 20 hours, with the most recently estimated error value used for each new flight. ~~The~~ Consideration of a long time constant is  
30 accordingly not problematic from the ~~safety-view~~ point of view of safety as ~~since~~ only comparatively slow changes in

the light wavelength need be expected.

Referring to Figure 2, the scale factors of the  
~~these~~ axes x, y and z are corrected or compensated for, in  
addition to specific bias error terms, for all three  
5 measurement axes in the system block 31 in order to correct  
system errors in the Kalman filter 30, to be precise,  
considering only one previously determined scale factor error  
for the vertical measurement axis z. The corrected data is  
then passed, together with acceleration data for all three  
10 axes x, y, z, to the navigation calculation 6, and the result  
is fed back with the GPS navigation data to the Kalman filter  
30.

The solutions and advantages of the invention can  
be summarized as follows:

15 1. In a GPS-supported inertial ~~track and~~  
attitude and heading reference system having a number of FOG  
sensors ~~which are~~ fed from a common light source, any scale  
factor error is compensated uniformly for all measurement  
axes using a Kalman filter technique with the aid of system  
20 information obtained from a measurement axis which is subject  
to relatively fast dynamics.

2. This error correction is preferably used with a  
long term constant to prevent short-term disturbance in the  
supporting sensor (e.g. the FOG sensor) for a vertical axis,  
25 and the possibly associated erroneous estimates from  
corrupting the inertial system. In order to prevent an  
incorrect estimate of a Kalman filter from corrupting the  
system, it is advantageous to introduce a limit for the

correction, and to emit a warning or a maintenance demand upon reaching such limit.

3. In contrast to other possible known or proposed solutions, the invention achieves a reliable reduction of the scale factor error for complete FOG systems, without incurring additional hardware costs.

The invention is thus based on the observation and finding that, although the scale factor can be determined for the vertical measurement axis of a three-axis inertial ~~track and~~ attitude and heading reference system, it cannot be estimated satisfactorily for the horizontal measurement axes. This ~~admittedly~~ results in good accuracy in the case of track changes, although large attitude errors occur in the presence of large attitude angle changes. ~~These problems can be reliably overcome by means of the invention.~~ Thus, in one advantageous embodiment of the invention, the scale factor error determined for the vertical z axis in a three-axis ~~track and~~ attitude and heading reference system is used for scale factor error correction, for error compensation for the other measurement axes x, y.

The invention links the technical capabilities of the Kalman filter with a modern FOG technology to achieve better utilization and to provide considerably better compensation of scale factor for all three measurement axes.

25 While the invention has been disclosed with reference to its presently-preferred embodiment, it is not limited thereto. Rather, it is limited only insofar as it is defined by the following set of patent claims and includes

within its scope all equivalents thereof.

## ABSTRACT

In a GPS-supported inertial ~~track and~~ attitude and heading reference system ~~which is~~ equipped with a Kalman correction filter ~~(30)~~ and ~~has~~ a multiple axis fiber optic gyroscope, the invention provides for only that scale factor error which is determined for the measurement axis (e.g. the vertical axis) ~~(z)~~ with relatively fast motion dynamics to be used as the Kalman filter correction value for the scale factor error correction for all the measurement axes ~~(x, y, z)~~ of the FOG ~~in order~~ to determine and compensate for the scale factor error caused by changes in the wavelength of a common light source ~~(1)~~. The ~~This~~ scale factor error correction is ~~advantageously~~ used only with a long time constant. ~~The invention ensures reliable correction for the scale factor for all measurement axes of the FOG system, to be precise without additional hardware complexity and only adaptation of the Kalman filter correction.~~